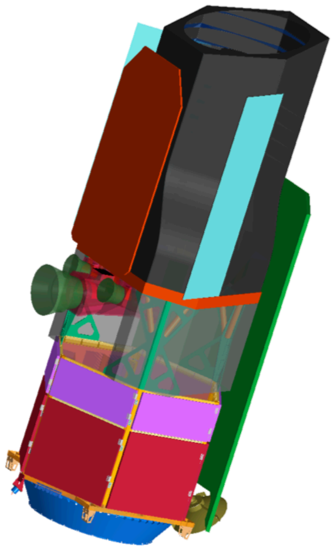
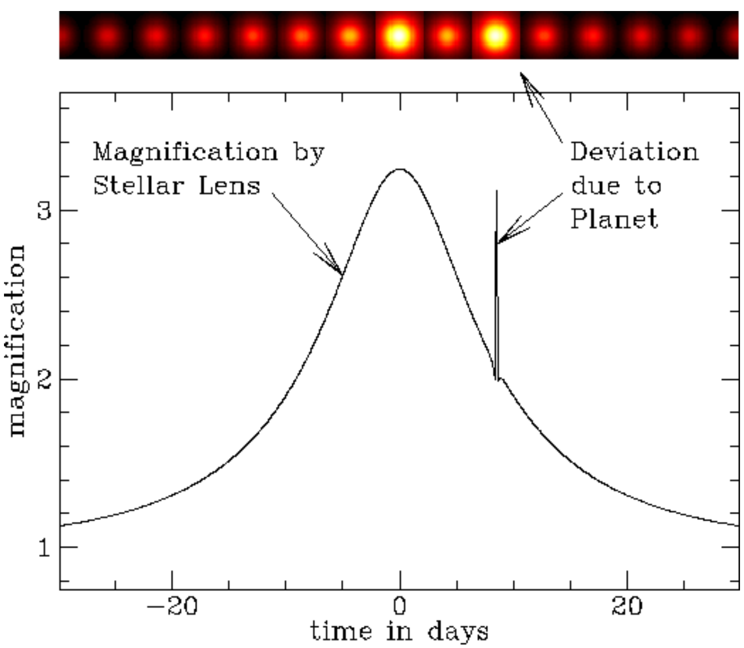
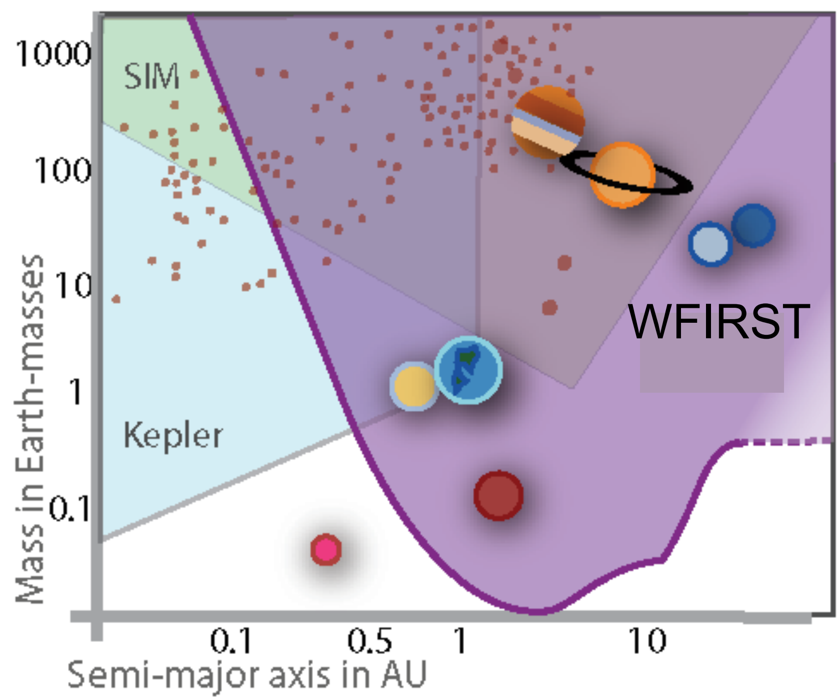


The WFIRST Microlensing Exoplanet Survey:

Figure of Merit

David Bennett
University of Notre Dame





WFIRST Microlensing Figure of Merit

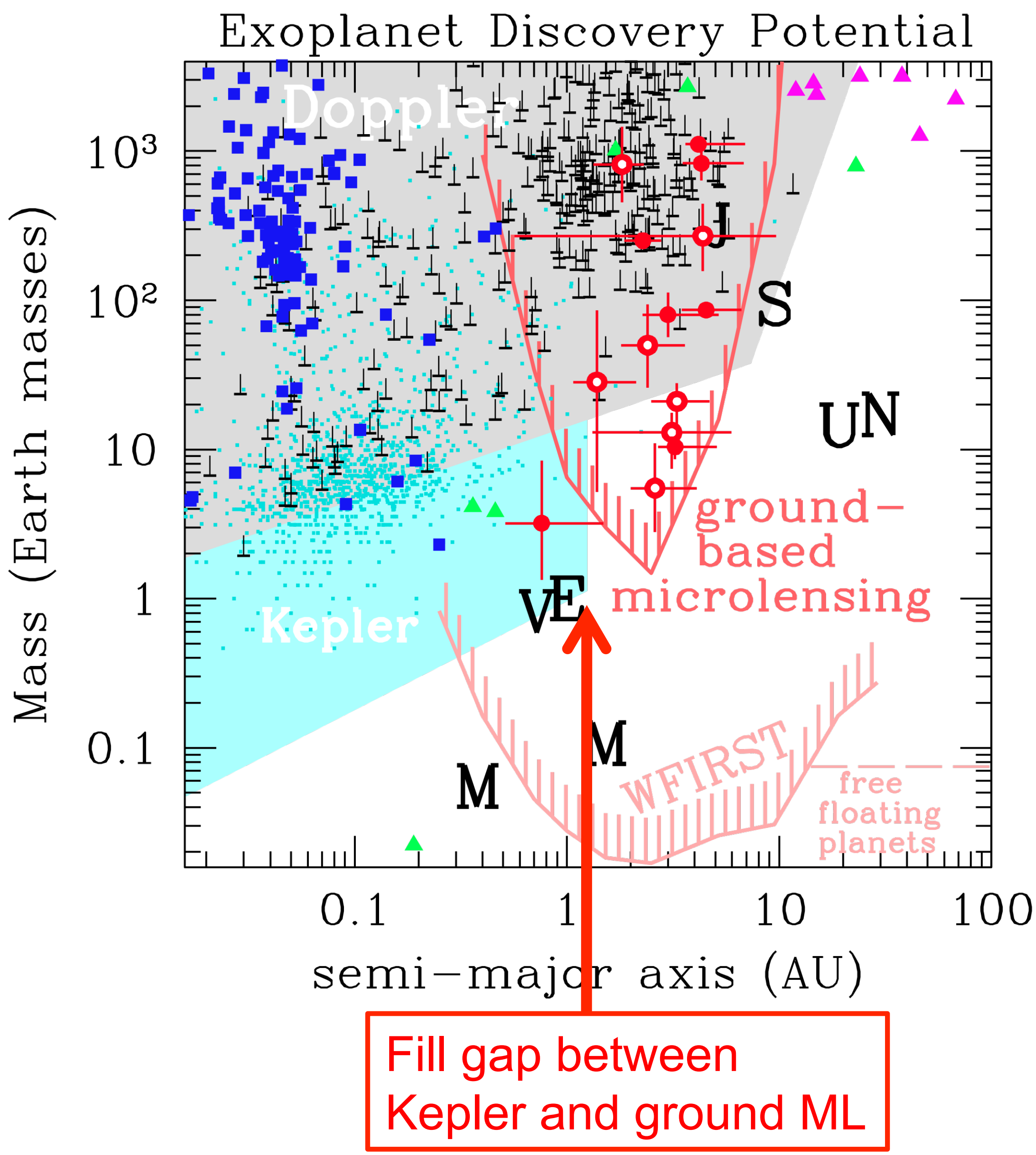
- Primary FOM1 - # of planets detected for a particular mass and separation range
  - Cannot be calculated analytically – must be simulated
    - Analytic models of the galaxy (particularly the dust distribution) are insufficient
  - Should not encompass a large range of detection sensitivities.
  - Should be focused on the region of interest and novel capabilities.
  - Should be easily understood and interpreted by non-microlensing experts
    - (an obscure FOM understood only be experts may be ok for the DE programs, but there are too few microlensing experts)
- Secondary FOMs (as presented by Scott)
  - FOM2 – habitable planets - sensitive to Galactic model parameters
  - FOM3 – free-floating planets – probably guaranteed by FOM1
  - FOM4 – fraction of planets with measured masses
    - Doesn't scale with observing time
    - Current calculations are too crude

Primary Microlensing FOM

- Number of planets detected (at $\Delta\chi^2$=80) with 1 M_{Earth} at 1 AU, assuming every main-sequence star has one such planet.
- For a 4 × 9 month MPF mission, this FOM~400. (Note MPF is 1.1m, ~0.65 sq. deg, 0.24” pixels)
- For nominal 500-day WFIRST microlensing program, decadal survey assumes FOM~200
- Alternative FOMs:
  – Number of planets detected (at $\Delta\chi^2$=80) with Earth:Sun mass ratio (3×10^{-6}) at 1 AU, assuming every main-sequence star has one such planet. Nominal WFIRST FOM~50
  – Number of planets detected (at $\Delta\chi^2$=80) with an Earth-mass planet in a 2-year orbit (not yet calculated). Period of a planet at R_E scales as $T_E \sim M^{1/4}$ instead of $R_E \sim M^{1/2}$

Planet Discoveries by Method

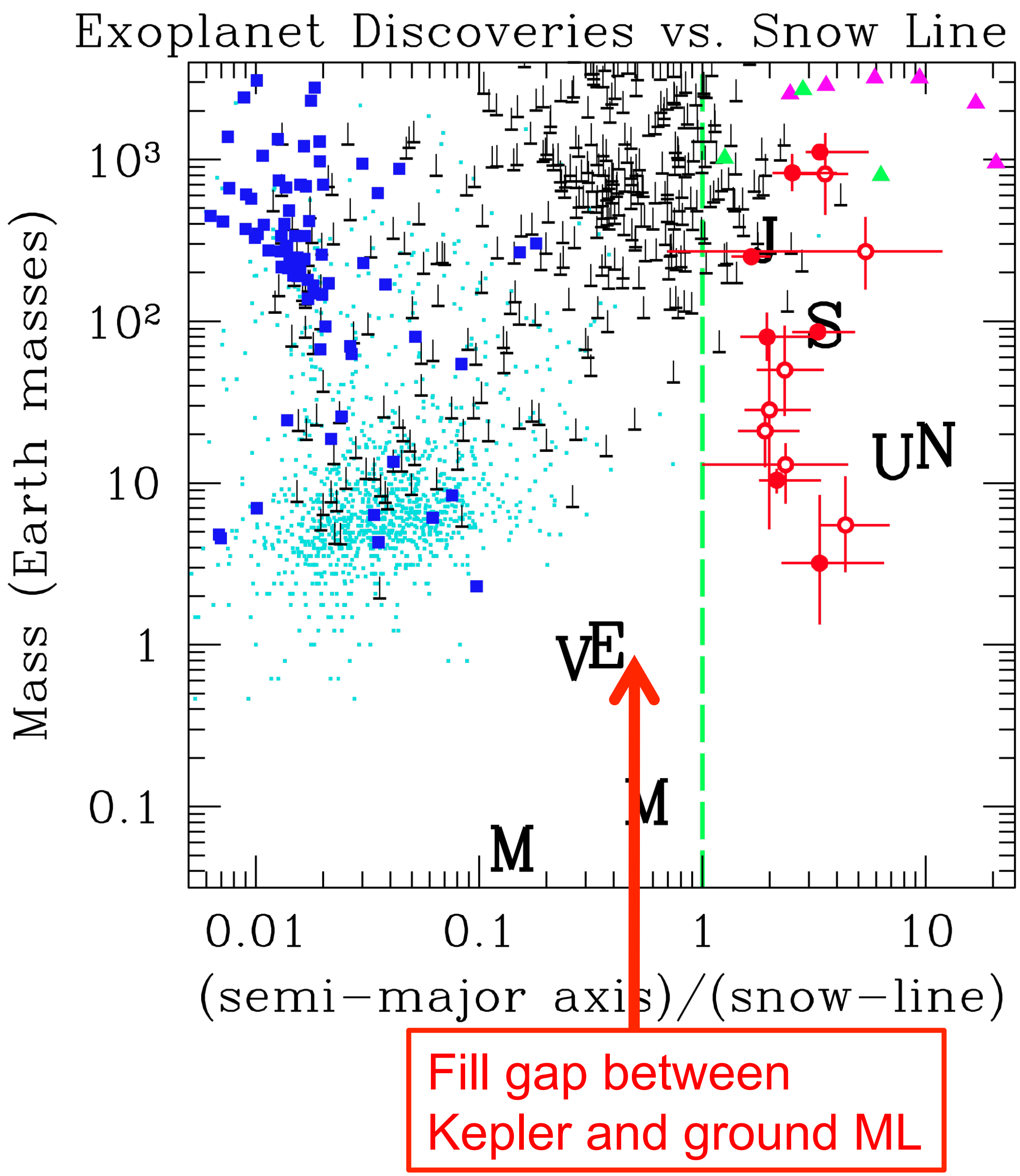
- ~400 Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
  - cool, low-mass planets
- Direct detection, and timing are magenta and green triangles
- Kepler candidates are cyan spots



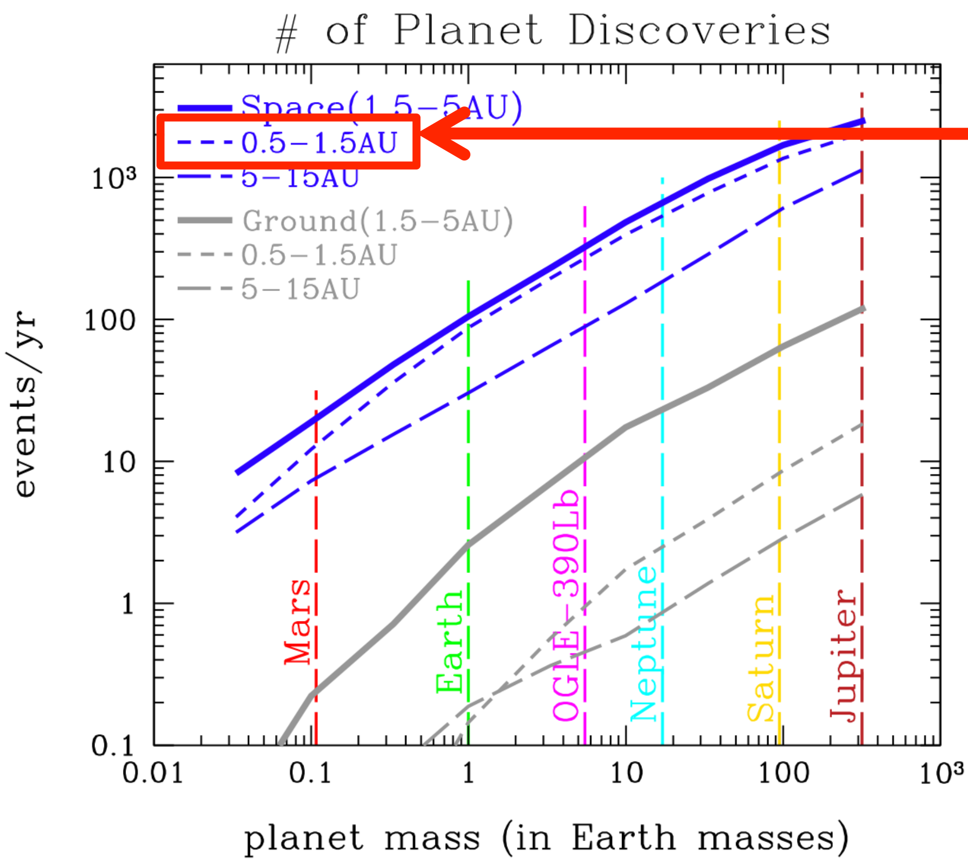
Planet mass vs. semi-major axis/snow-line

- "snow-line" defined to be 2.7 AU ($M/M_{\odot}$)
  - since L$\propto$ M^2 during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles
- Kepler candidates are cyan spots

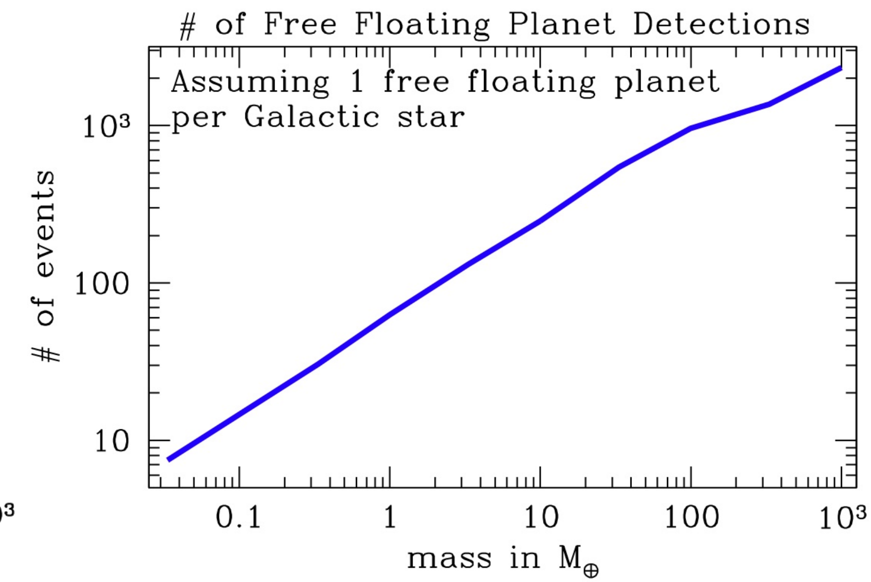
- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



WFIRST's Predicted Discoveries



Pick a separation range that cannot be done from the ground; wider separation planets will also be detected.



The number of expected WFIRST planet discoveries per 9-months of observing as a function of planet mass.

Microlensing "Requires" a Wide Filter

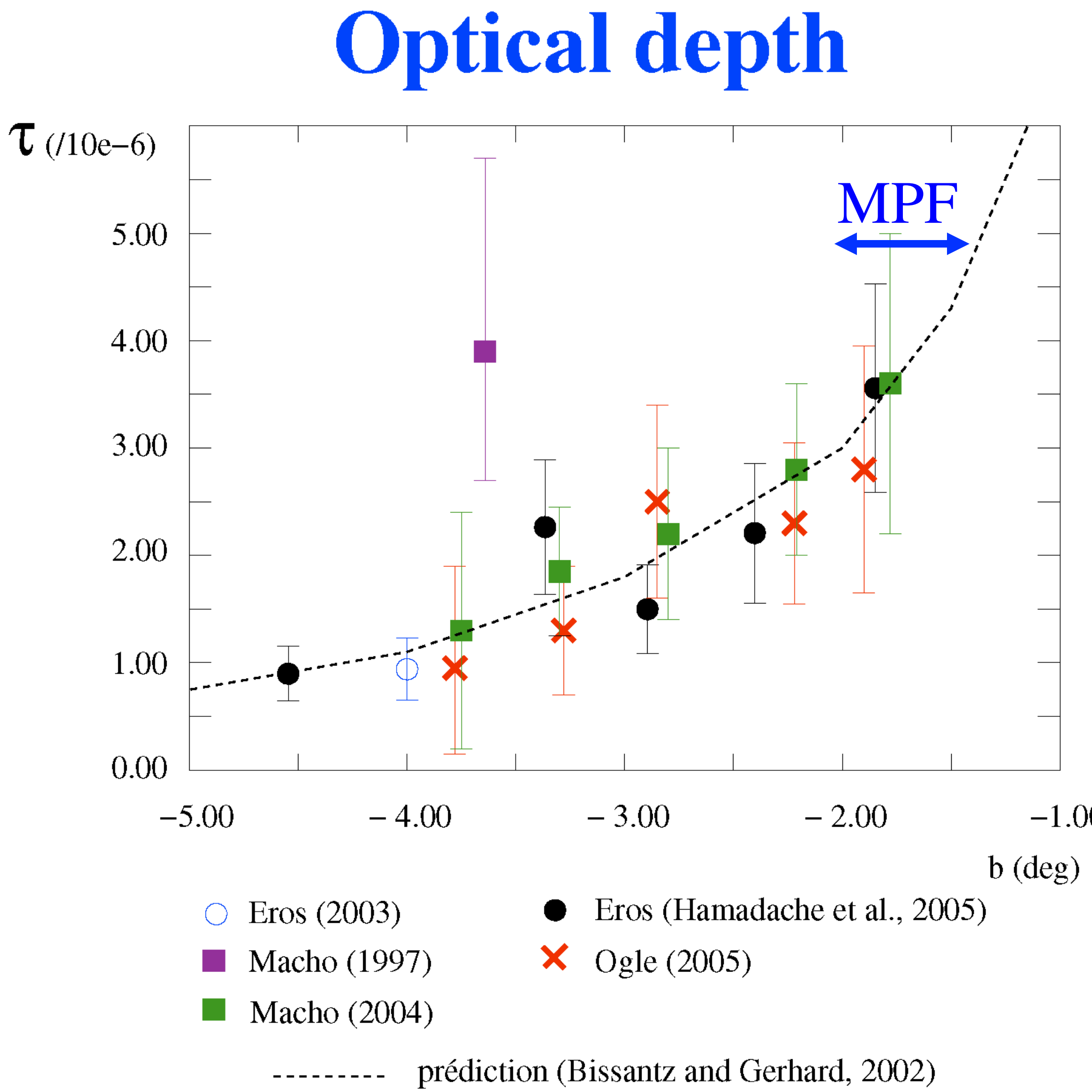
- Roughly 1.0-2.0 μm
- In principle, this is negotiable
- In practice, probably not
  - Exoplanet program is "equally important" to DE program – so it should probably get to select at least 1/5 filters
  - WL has requested 3 IR passbands, BAO needs spectra, SNe can probably live with 3 WL filters
  - Rough guess: FOM reduction by ~25% with a WL filter
    - So, DE programs should consider if this filter is worth 125 days of DE observing time
- Multiple filter options => much more simulation work
  - Field locations & Observing Strategy
  - Throughput
  - PSF size

Mission Simulation Inputs

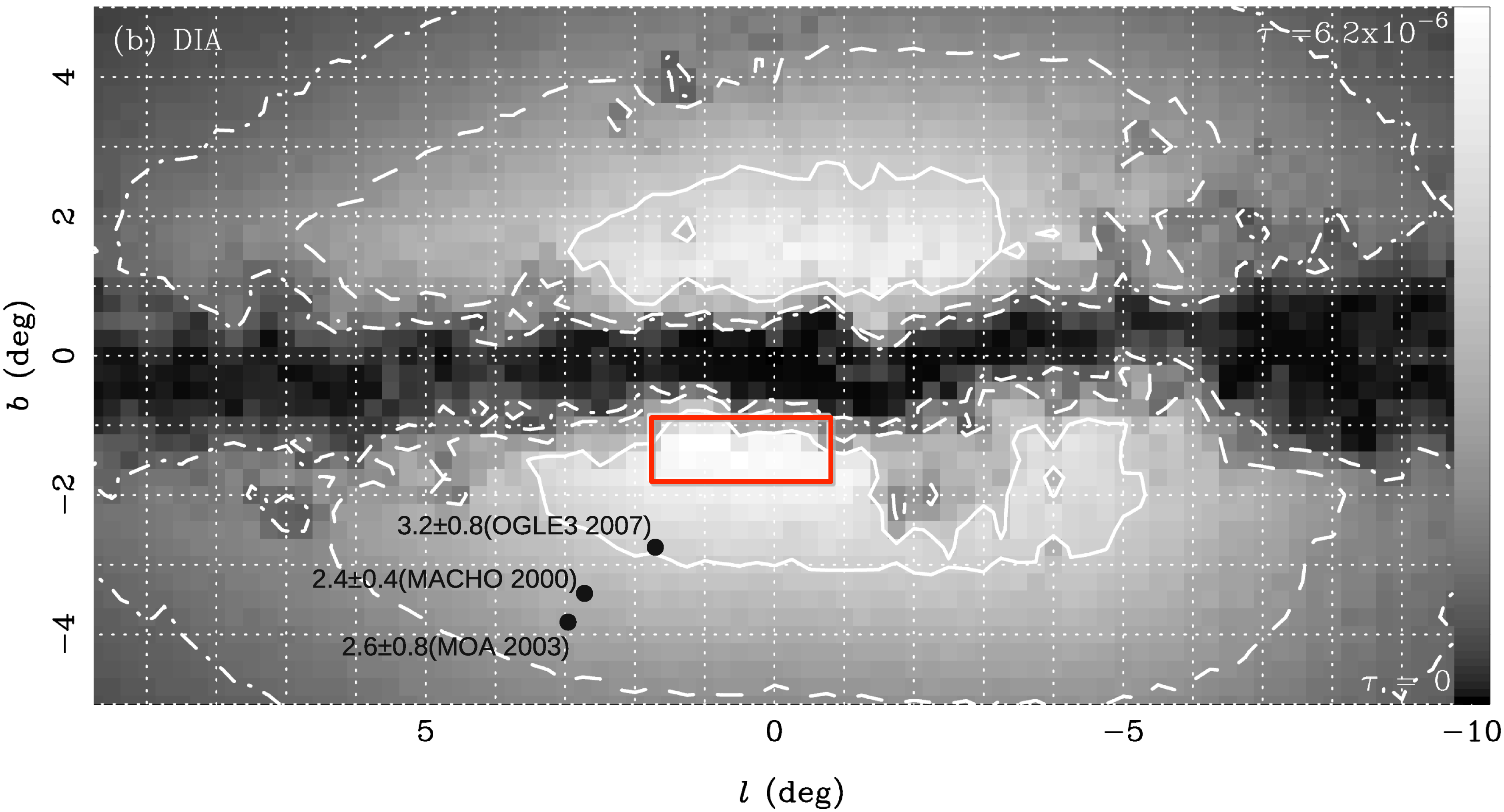
- Galactic Model
  - foreground extinction as a function of galactic position
  - star density as a function of position
  - Stellar microlensing rate as a function of position
- Telescope effective area and optical PSF
- Pixel Scale – contributes to PSF
- Main Observing Passband ~ 1.0-2.0 μm
  - throughput
  - PSF width
- Observing strategy
  - # of fields
  - Observing cadence
  - Field locations

Microlensing Optical Depth & Rate

- Bissantz & Gerhard (2002) τ value that fits the EROS, MACHO & OGLE clump giant measurements
- Revised OGLE value is ~20% larger than shown in the plot.
- Observations are ~5 years old



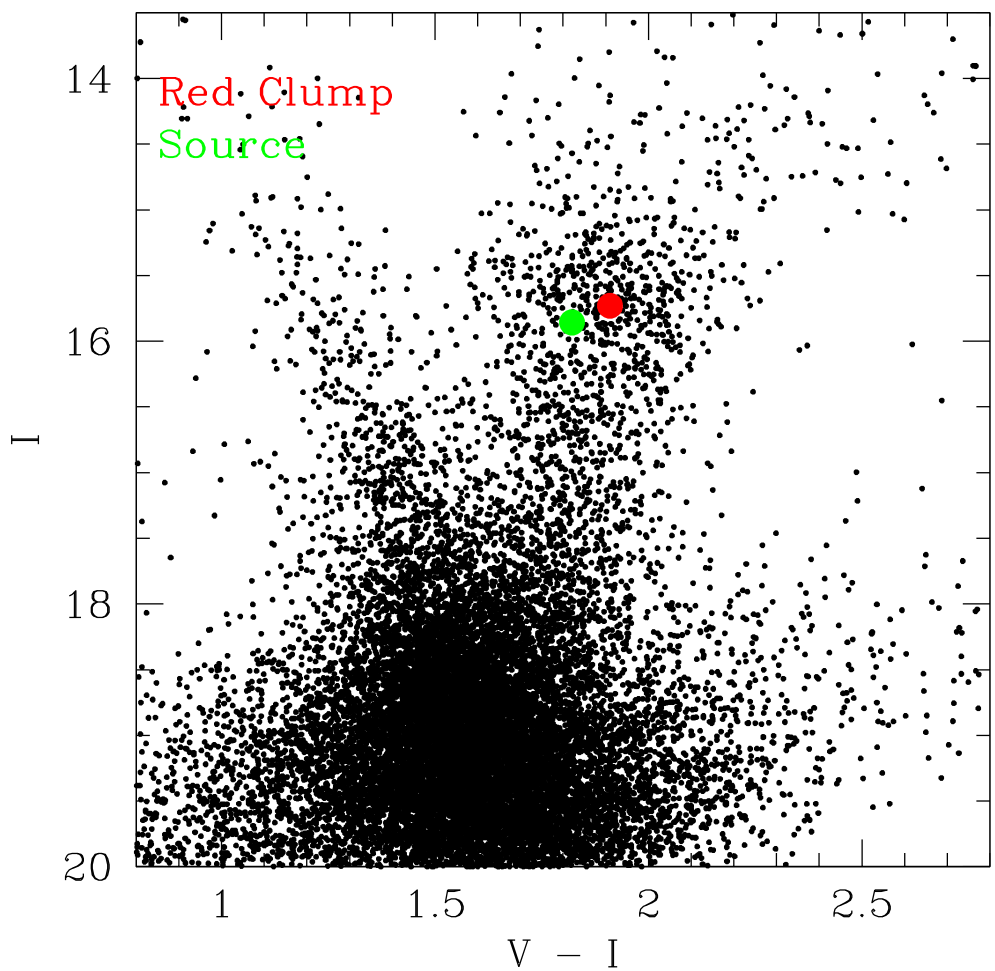
Select Fields from Microlensing Rate Map
(including extinction)



Optical Depth map from Kerins et al. (2009)   - select more fields than needed

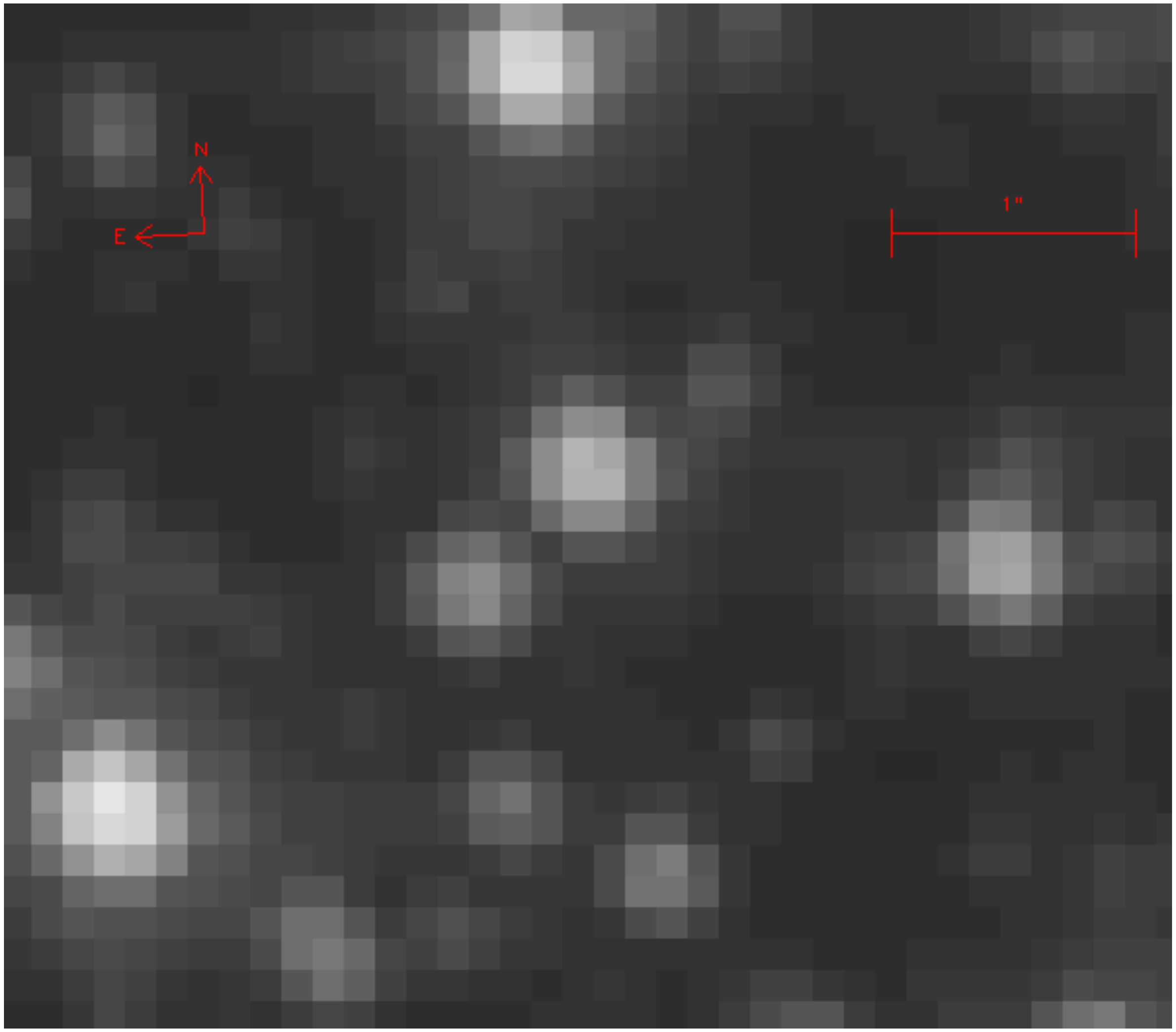
Determine Star Density

- Match Red Clump Giant Counts for selected fields
- Varies across the selected fields
- Use HST CM diagram for source star density



Create Synthetic Images & Simulate Observing Program

- Simulate photometric noise due to blended images
- Depends on
  - Star density
  - Pixel scale
  - Passband
  - Telescope design
- Simulate Microlensing light curves
  - Depends on observing cadence
- Identify simulated light curves with detectable planetary signals
- Determine planet detection rate



Parameter Uncertainties

- Send simulated light curve data to Scott Gaudi (and Joe Catanzarite from JPL-WFIRST Project Office)
- They estimate parameter uncertainties using a Fisher-Matrix method
- Evaluate planet discovery penalties from interruptions of observations

Future Work (2nd SDT Report)

- Use lens star detection and/or microlensing parallax to determine host star masses
- Add this to Fisher matrix parameter uncertainty estimates

mass-distance relations:

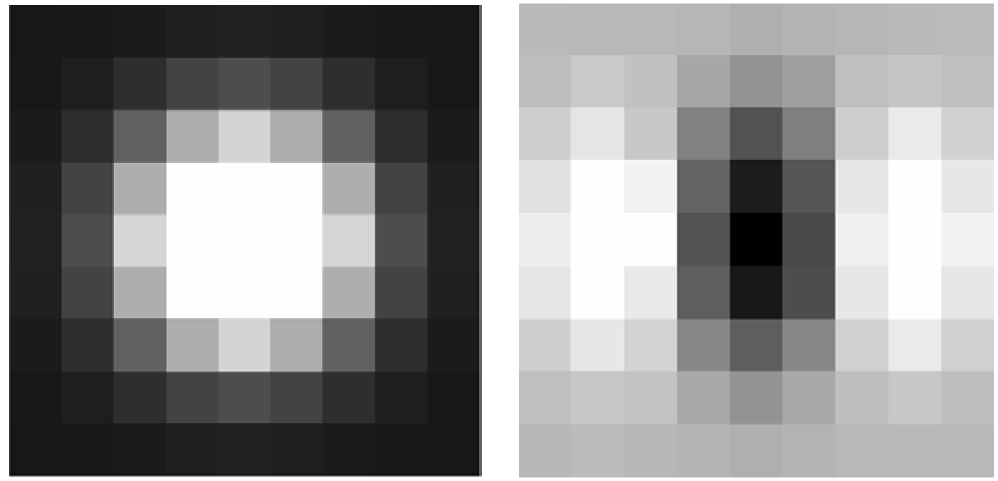
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

Simulate Lens Star Detection in WFIRST Images

Denser fields yield a higher lensing rate, but increase the possibility of confusion in lens star identification.



A 3× super-sampled, drizzled 4-month MPF image stack showing a lens-source blend with a separation of 0.07 pixel, is very similar to a point source (left). But with PSF subtraction, the image elongation becomes clear, indicating measurable relative proper motion.

Microlensing Tracibility Matrix

Presumably required for June report draft from Jonathan Lunine:

Foundational Questions	Science Goals		Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Quantity to measure	Instrument Functional Requirements	Mission Requirements	Implementation requirements
G1 Is our solar system typical or rare among planetary systems?	SO1	Determine the occurrence and architectures of planetary systems across a significant portion of the Galaxy	Make a definitive measurement of the frequency of bound planets and their masses with separations of 0.5 AU and larger	Provide the ability to detect at least 1000q planets of Uranus mass or larger, where q is the fraction of stars with planets in the 0.5-2.5 AU region.	Large number of stars, Stellar brightness variation to XX %	Monitor > 0.5 billion star-years of Galactic bulge stars brighter than J=23	Aperture size 1.1 m FOV 0.65 sq. deg Wavelength 600-1700 nm Detector performance QE > 70% 900-1400 nm; >50% 700-1600 nm Exposure time 2.8 min/field Focal plane 150 Megapixels 4 pointings.	
				Measure planet masses to 20% accuracy		Observe at least once per 15 minutes for 80% of the time for periods > 20 days.		
				Measure separations and mass ratios to 10% accuracy.		Photometric accuracy better than 1% for a 2.8 minutes exposure of a J=19.9		
						Better than 0.3" angular resolution to resolve the brightest main sequence stars		
	S02	Determine the dynamical histories of planetary systems	Detect a sufficient number of free-floating planets and measure their masses so as to understand the statistical occurrence of planetary ejections	Detect at least 1000y free-floating planet events, where y is the number of free floating planets per star in the Galaxy				
				Measure free-floating planet masses to 50% accuracy.				
G2 –Are potentially habitable worlds common in the Galaxy?	SO3	Determine the frequency of occurrence of Earth-mass planets in and near the habitable zone	Make a definitive measurement of the frequency of bound planets in the Earth-Mars mass range with separations of 0.5 AU and larger	Provide the ability to detect at least 200r planets of mass between that of Earth and Mars, where r is the fraction of stars with Earth-to-Mars-mass planets in the 0.5-2.5 AU region.	Large number of stars. Stellar brightness variation to YY%.		Aperture size 1.1 m FOV 0.65 sq. deg Wavelength 600-1700 nm Detector performance QE > 70% 900-1400 nm; >50% 700-1600 nm Exposure time 2.8 min/field Focal plane 150 Megapixels 4 pointings.	
				Measure terrestrial planet masses to 20% accuracy				
			Determine with sufficient accuracy the semi-major axes of terrestrial planets, and the stellar type, so as to determine the habitability of said planets.	Measure separations within the habitable zone and masss ratios to 10% accuracy.				
			Determine the frequency of free-floating super-Earth planets to assess the maximum possible number of free-floating habitable "Stevenson" worlds.	Measure free-floating planet masses to 50% accuracy.